FINAL TECHNICAL REPORT

INVESTIGATION OF CASCADIA EARTHQUAKE TRIGGERED LANDSLIDES:

COLLABORATIVE RESEARCH WITH THE OREGON DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES (DOGAMI) AND THE UNIVERSITY OF OREGON

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1.0 ABSTRACT

Large magnitude earthquakes in mountainous settings commonly trigger thousands of landslides and a significant proportion of the quake-related damage and casualties arises from these slope failures. In western Oregon and Washington, we lack historical documentation of large earthquakes, but the geologic and topographic signature of landsliding is pervasive, as steep topography and weak lithologic units combine to promote slope instability over a range of timescales. The plethora of ancient (or inactive) deep-seated landslides suggests that the conditions promoting pervasive deep-seated instability have not been realized in recent decades or longer. In short, no landslide in Oregon has been definitively tied to a Cascadia megathrust earthquake. Testing potential linkages between great earthquakes and landslides is fundamental for understanding the hazard and risk of these subduction zone events as well as optimizing risk reduction activities. Thus, we sought to determine whether the timing of deep-seated landslides is consistent with the 10,000-yr earthquake chronology in the region as well as refine the techniques required to establish such a connection.

Standing dead forests can be found in dozens of landslide-dammed lakes dispersed across western Oregon and provide an ideal site for assessing landslide provenance due to a Cascadia megathrust earthquake. Using lidar data, we identified >200 landslide dams with youthful appearance and potentially dateable sedimentary deposits. To determine the age of the landslide dams, we used dendrochronology (tree ring analysis) of standing snags in the lakes to establish the year of lake (and thus landslide) formation. The approach used involved mining reference tree ring records from coastal Oregon and the central Coast Ranges and Cascade Ranges that reveal consistent patterns due to regional climate variations. Our preliminary efforts for Wasson, Klickitat, and Lobster Lakes demonstrate that the landslide damming event occurred in 1819AD, 1751AD, and post-1738AD, respectively. Although these dates do not correspond with a known Cascadia megathrust event, they highlight the accuracy and potential of the method and we are in the process of applying these methods to >10 additional sites in western Oregon. At Wasson Lake, we improved this approach by combining the ^{14}C calibration curve and radiometric dates for selected tree rings to confirm our dendrochronology results. In addition, we initiated radiometric dating of detrital organic materials entombed in landslide deposits for several of our slide-dammed lakes. This enables us to establish the typical inheritance (or pre-slide age) of organic materials in the region, which is useful for a range of paleoseismology and geomorphic investigations.

2.0 PROJECT DETAILS

Coseismic landslides have caused significant damage and losses around the world and will almost certainly cause considerable damage to the Pacific Northwest (PNW) following a Cascadia Subduction Zone (CSZ) earthquake (Allstadt et al., 2013). This is especially true in areas like the PNW coastal region, characterized by steep slopes and loose sediments and is extremely susceptible to landslides (Burns et al., 2016). In a recent publication, Burns and Mickelson (2013) estimated that the damage from coseismic landslides in the City of Astoria, a small coastal community in Oregon, might approach the damage and losses caused by the earthquake itself. The study estimated losses from the earthquake shaking to be approximately $341M and losses from earthquake-triggered landslides to be $260M. Similarly, during the 1964 Alaska subduction zone earthquake, landslides were responsible for more than half the damage (Keefer, 1984). The 2008 Wenchuan Earthquake caused more than 15,000 landslides, which resulted in about 20,000 deaths (Yin, et al., 2009). Wartman and others (2013) found an astonishing 3,477 landslides in Japan associated with the 2011 Tōhoku earthquake. Although megathrust events have triggered thousands of landslides during recent subduction zone earthquakes, no studies have developed a causal link between previous great CSZ earthquakes and terrestrial landslides in the Cascadia region. Despite compelling

speculation (Atwater, et al., 2005; Schultz et al., 2012; Karlin et al., 2004; Morey et al., 2013; Blais-Stevens et al., 2011; Witter et al. 2003; ODOT, 2015), no research and publications directly dating and/or linking movement of landslides in Oregon to CSZ earthquakes have emerged as of yet. Establishing such links between subduction zone great earthquakes and landslides is fundamental for understanding the hazard and risk of these events as well as optimizing risk reduction activities.

Because there is already a comprehensive CSZ earthquake record based on paleosol, tsunami, and turbidite deposits (Atwater et al., 2015; Goldfinger et al., 2012; Goldfinger et al., 2015; Witter et al., 2013), especially the very well constrained last event on January 26, 1700, there is a great opportunity to exploit this record to determine whether some landsliding in the Oregon Coast Range (OCR) tends to result from seismically-induced ground shaking. The purpose of this study was to compare individual landslide event dates to the existing CSZ earthquake chronology to see if landslides have been triggered during major earthquakes, particularly the 1700AD event (Figure 1).

Figure 1. Photo of Brian Atwater example of a tsunami deposit from the 1700 event. Photo of a "ghost forest" on the Washington Coast. Trees killed by the 1700 Cascadia megathrust earthquake.

2.1   Background

The Oregon Department of Geology and Mineral Industries (DOGAMI) has begun the immense job of mapping existing landslides in Oregon using lidar derived topographic data. In the past 8 years, DOGAMI has mapped or compiled approximately 30,000 landslides in Western Oregon (Figure 2). Previously, the pervasive forest cover precluded us from definitively mapping deep-seated slides.   Critically, however, the triggering mechanisms of almost all of these landslides are unknown, and our study aims to determine if earthquakes play a central role in the generation and reactivation of deep-seated slides. In order to understand the complete impact of earthquakes on social, built, and natural assets of our region, we must better understand the correlation between the earthquakes and the landslides.
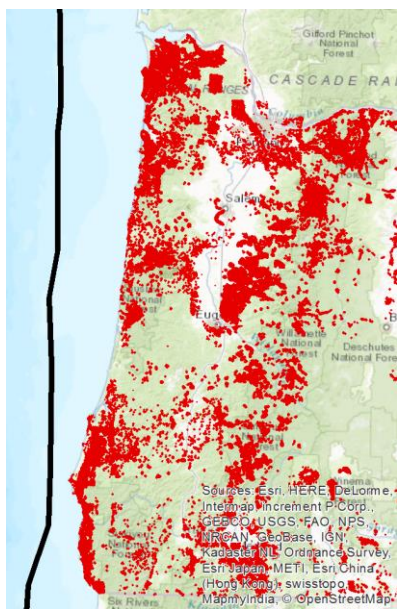
Figure 2. Map of western Oregon with landslide polygons from SLIDO 3.3 (Burns, 2014)

2.2 Study Area

The study area for this project is the Oregon Coast Range (OCR) located in western Oregon. The OCR is a forearc mountain range stretching from the Columbia River to the Coquille River and separates the Pacific Ocean from the Willamette Valley (Orr et al. 1992). The Pacific Ocean is the primary climate driver in the coastal ranges by modulating temperatures and delivering an annual average of over 100 inches of precipitation along the western slopes. This combination results in dense, closed canopy coniferous vegetation.

The geology in the OCR is primarily comprised of marine sedimentary formations with limited volcanic and intrusive outcrops. The marine sedimentary rocks are particularly susceptible to landslides mostly because they are relatively weak and have an abundance of weak planes such as bedding, faults, and fractures. Uplift since the Miocene owing to convergence along the Cascadia subduction zone has led to valley incision and the evolution of steep hillslopes. In areas of moderate (>10 degree) tilting of the sedimentary units, such as along the flanks of low-amplitude folds in the central OCR, large (area >0.5 km^2) dip-slope landslide failures are common (Roering et al., 2005).

Recent light detection and ranging (lidar) based landslide inventory mapping (Burns and Madin, 2009) in the OCR has greatly expanded our knowledge of landsliding. For example, in the Big Elk Creek Watershed in the OCR, landslide mapping in the 1970s identified 37 landslides, whereas recent lidar based mapping revealed an astonishing 1,517 landslides (Burns et al., 2012). This implies that we previously recognized approximately 2% of the existing landslides.

Subduction zones can produce earthquakes greater than M8.5, and are the setting for the largest recorded earthquakes on Earth. The last known megathrust earthquake in the northwest was on January 26, 1700, 317 years ago (Atwater et al., 2015). Geological evidence indicates that Cascadia megathrust earthquakes have occurred many times prior with an average return interval of ~530 years, and a range of 100 years to 1,200years (Witter et al., 2010). Recently, Goldfinger and others (2016) provided a revised assessment for the central to northern Oregon coast, which was found to have a mean recurrence time of ~340 years.

Comparison of the history of subduction zone earthquakes along the Cascadia Subduction Zone in northern California, Oregon, and Washington, with events from human history. Ages of earthquakes are derived from study and dating of submarine landslides triggered by the earthquakes. Earthquake data provided by Chris Goldfinger, Oregon State University; time line by Ian P. Madin, DOGAMI.
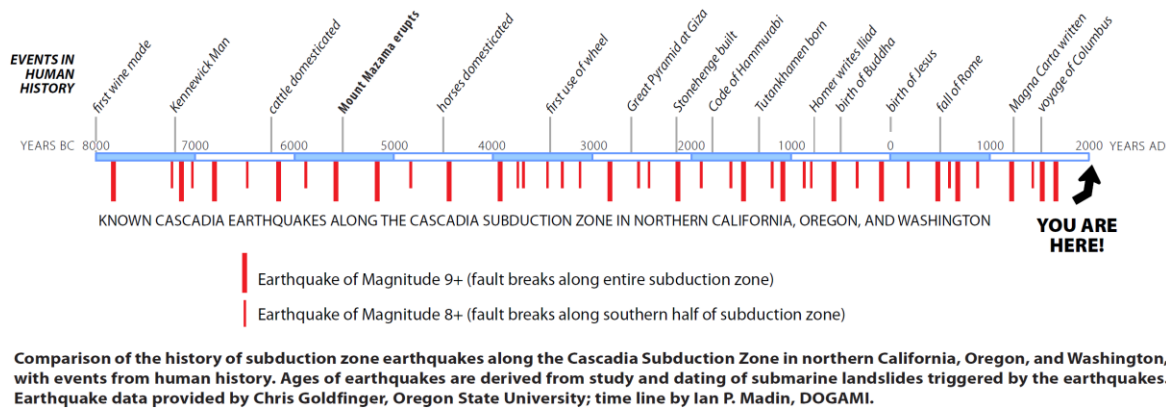
Figure 3. Cascadia Subduction Zone earthquake history (after Madin, 2010).

2.3 Methods

In our proposal, we planned to undertake the following three tasks in order to begin documentation of past earthquake-triggered landslides in Western Oregon: 1) Site selection, 2) Field work and sample collection, and 3) Chronology of landslide material and horizons. We proposed to use a variety of numeric and qualitative dating techniques to establish the age of the landslide to test for correlation to CSZ earthquakes, specifically the 1700AD event. The proposed fieldwork was focused on 1) excavating test pits and trenches across exposed valley fill sediments, 2) documenting the trench stratigraphy using traditional paleoseismology methods, 3) sampling organic material from horizons that reflect stream damming periods, and 4) processing organic materials for radiocarbon dating to constrain the age of each landslide-dam event. During our initial reconnaissance visits to several sites, the ruggedness of the terrain and inaccessibility of the impounded upstream valleys made it apparent that traditional trenching with an excavator would be problematic and even dangerous. As a result, we changed our approach and rather than use mechanized means we exploited channel banks incised into landslide deposits to access organic material for dating. Our initial investigations also revealed the prevalence of lakes upstream of several landslide dams that could also be used to establish accurate chronologies of landslide timing using dendrochronology. Thus, we shifted our main emphasis from trench-based investigation to dendrochronology (suggested as a possible alternate technique in our original proposal) and enlisted the expertise of Professor Bryan Black, University of Texas, an expert in dendrochronology in the Pacific Northwest. Combined with landslide deposit ages, our analysis enables us to test if individual landslide event dates correlate to the existing CSZ earthquake chronology and particularly the 1700AD event. With that goal, we performed four primary tasks: 1) Site selection, 2) Field work and sample collection, 3) laboratory analysis, and 4) chronology of landslides.

2.3.1 Site Selection

By scanning bare earth lidar datasets, we identified 219 landslides that featured rough (and thus relatively young) landslide deposits that had impounded small streams and were likely to be favorable for preserving drowned trees (Figure 4). From our initial set of 219 sites, selected from over 10,000 deep-seated landslides in western Oregon, we filtered the list of candidate sites to 29 by identifying those with the following characteristics (Figure 5):

- Landslides with morphologic evidence of recent movement;
- Features such as a sharp headscarps, and lack of defined channels on the deposit are indicative of a young landslide (Booth et al., 2009);

- Similar morphology to landslides of known age that occurred before and after the 1700AD event, including the 1976AD Drift Creek Landslide and the 800AD Loon Lake Landslide;
- Publicly owned lands;
- Ease of access (i.e., roads close to site); and,
- Proximity to the coast to increase likelihood that coseismic shaking induced failure.

Additionally, we prioritized sites with:
- Incised deposits that permit access to landslide deposit stratigraphy;
- Upstream sedimentary deposits that permit hand augering or coring for sample collection; and,
- Lakes with standing snags or stumps.
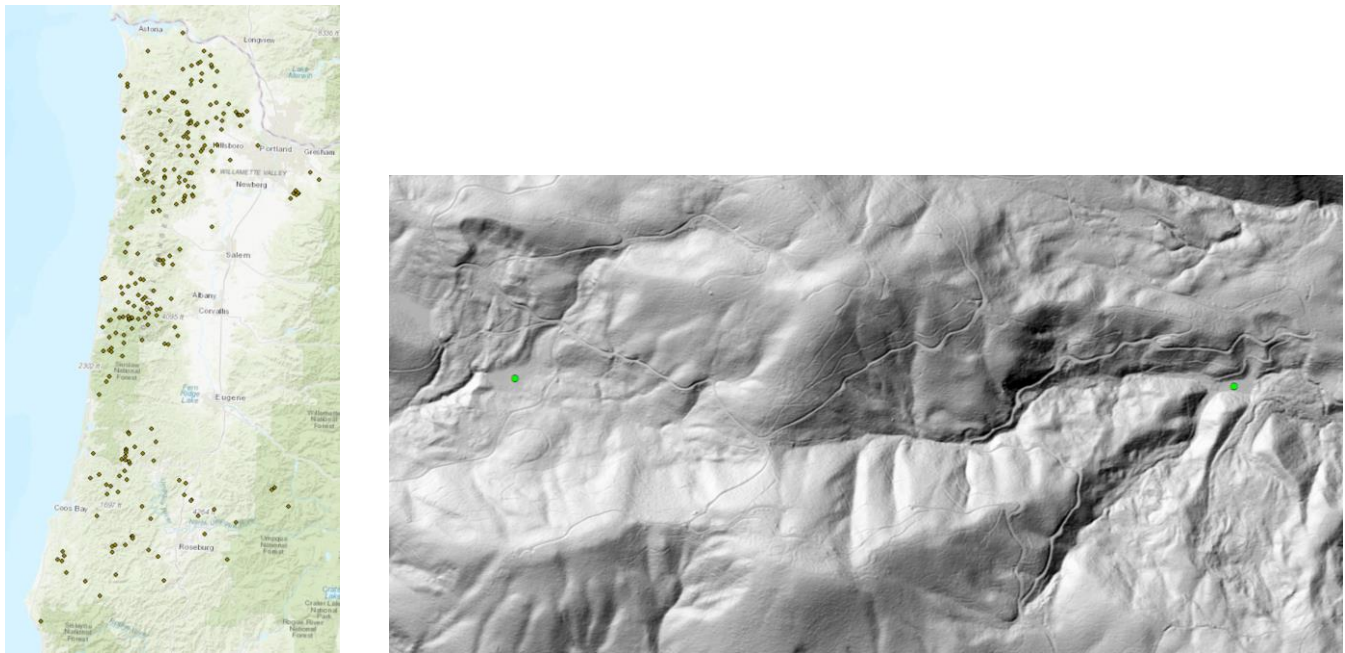
Figure 4. Map of 219 candidate sites (brown dots) in the Oregon Coast Range (left). Map of two examples of candidate sites (2 green dots) with bare earth lidar hillshade (right).
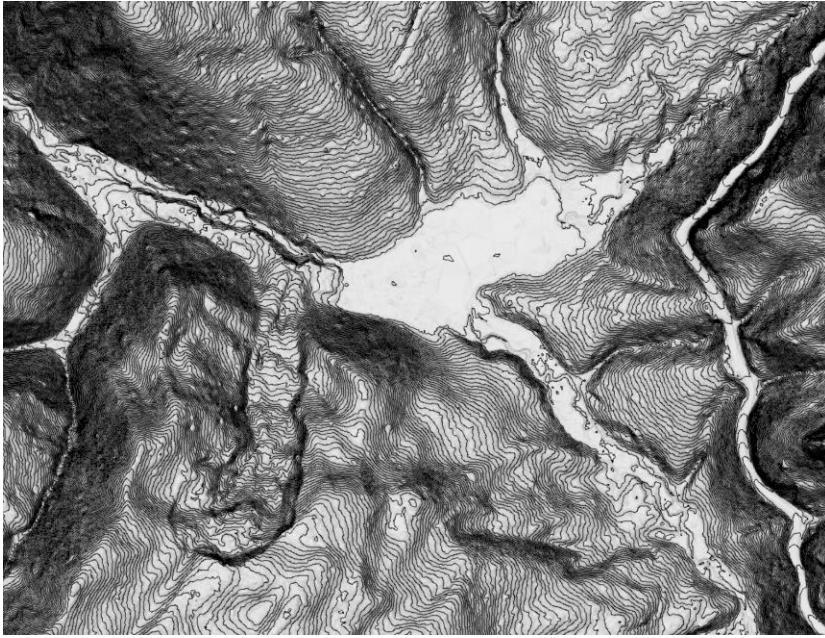
Figure 5. Bare earth lidar hillshade and contours of the Wasson Lake site, one of the 29 candidate sites.

2.3.2 Field Work, Sample Collection, and Detailed Map Creation

Having identified multiple landslide impounded lakes, we performed preliminary site reconnaissance and site visits at 19 of the 29 candidate sites to evaluate the potential of the site for future detailed mapping and sampling (Figure 6). During the field visit we observed the following:

- Morphology of the landslide;
- Presence of a lake;
- Presence of tree snags (ghost forest) in lakes or sedimentary deposits and potential for dendrochronology;
- Presence of old growth trees on the landslide deposit for dendrochronology;
- Potential for coring or augering of sedimentary deposits upstream of landslide dams and within landslide deposits;
- Potential anthropogenic activity that may preclude an earthquake linkage or obscure landslide morphology; and,
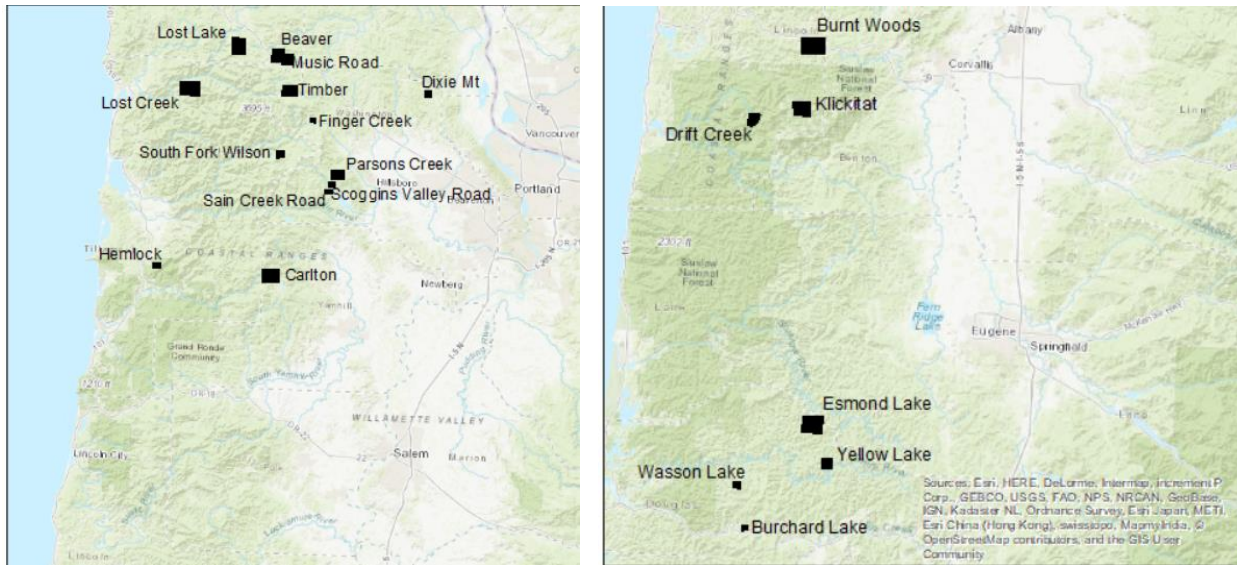- Accessibility.

Figure 6. Eighteen sites where site reconnaissance was performed. Northern Coast Range on left and southern Coast Range on right.

Table 1. Site details including name, land ownership, and status of investigation.

GIS OBJECTID	Site Name	Land Owner	Site Status
1	Beaver	State or Oregon and Longview Fiber	reconnaissance; beaver dam at site, deemed not optimal
2	Lost Lake	State of Oregon, Longview timberlands	reconnaissance; C14; detailed map
3	Timber	ODF Land	reconnaissance; C14; detailed map; auger
4	Carlton	BLM and City of McMinneville	reconnaissance; C14; detailed map
6	Dixie Mt	BLM	reconnaissance; C14; site deemed not optimal
8	Lost Creek	ODF Land	reconnaissance; C14; detailed map
10	South Fork Wilson	State of Oregon	reconnaissance; C14; detailed map; auger; live dendro
11	Sain Creek Road	Stimson	reconnaissance; C14; detailed map; auger
12	Parsons Creek	Stimson	reconnaissance; C14; detailed map
15	Hemlock	USFS, BLM	reconnaissance; C14; detailed map; auger
19	Music Road	State of Oregon	reconnaissance; C14; auger; detailed map
20	Scoggins Valley Road	Stimson	reconnaissance; detailed map; live dendro
21	Wasson Lake	BLM	reconnaissance; C14; snag dendro; detailed map; sed vol rate
22	Burchard Lake	BLM/Roseburg	reconnaissance; C14; snag dendro; detailed map; auger; sed vol rate
23	Yellow Lake	BLM	reconnaissance; C14; snag dendro; detailed map
24	Klickitat	Weyerhaeuser	reconnaissance; C14; snag dendro; detailed map; auger; live dendro

25	Burnt Woods	BLM	reconnaissance; man-made concrete dam; site deemed not optimal
26	Esmond Lake	BLM/Roseburg	reconnaissance
27	Drift Creek	BLM	sed vol rate; known failure date-1976

Notes:

reconnaissance – Visited site and inspected landslide and dammed sediment and lake areas

C14 – Acquired samples for C14 dating

snag dendro – Sampled snag (dead trees, ghost forest trees) trees in the dammed sediment/lake areas for dendrochronology

detailed map – Created a detailed site map (see Figure 7 example)

auger - Explored subsurface with a hand auger

live dendro – Sampled live old growth trees on the landslide deposit for dendrochronology

sed vol rate – Conducted sediment volume rate analysis to estimate date range

During the initial site reconnaissance at some sites, it was immediately apparent that several sites had been affected by either anthropogenic or biological factors and were subsequently excluded from further consideration. Those sites included Beaver (impounded by a large beaver dam), Burnt Woods (had a concrete dam/levee), and Dixie Mt (appeared to have been influenced by land use activities). This left 19 sites for which we performed site work, sampling, and detailed mapping; an example of a detailed site map is shown in Figure 7. These maps enabled us to capture site variability, search for potential landslide event horizons, and increase the likelihood of finding datable material. Detailed site descriptions were generated, including: dates visited, access, topography, landslide description, lake area, sampling, and interpretations.

At several sites, we performed subsurface exploration in the upstream sediments with a hand auger to identify buried paleosols, the original forest (litter? ground?) surface prior to the occurrence of the landslide and sediment infill. In addition, measurements of the sediment thickness and sediment properties within the 'infill' were undertaken to identify the original (or buried) forest floor. This was important since it enabled us to identify the presence of organic material that could be acquired for carbon dating. Samples of the surface or near surface organic material in the landslide deposits and drowned trees were also obtained for radiocarbon dating. These samples ranged from small to large detrital woody debris to tree ring samples taken from the tree snags.

Wood samples from drowned trees in landslide-impounded lakes were subsequently ^{14}C dated at Lawrence Livermore National Laboratory's Center for Accelerated Mass Spectrometry (LLNL CAMS) to provide an approximate calendar year of death (+/-20 yr). The calendar year of death, and thus of the landslide damming event, was then established using dendrochronology to cross check the dates. This approach assumes that some aspect of the environment limits tree growth (e.g. summer drought) and as this variable fluctuates from year to year, produces a synchronous pattern or growth 'bar code' among samples of a given species and region. To date, three Douglas-fir chronologies >400 yr have been generated by Black et al. (2015) for the Oregon Coast Range, and four > 800 yr chronologies in the western Cascade Mountains. Each of these chronologies was obtained from living trees and provides a means to crossmatch against the patterns observed from the undated ghost forests.

To establish landslide dates, multiple samples within each lake (up to five at Klickitat Lake) were prepared with increasingly fine sandpaper and lapping film to reveal the cellular structure of the wood. Although calendar years are unknown for these samples, they could be crossdated against one another within each lake. This crossdating and replication ensured that all micro- or "false" rings had been correctly identified for each sample, and that increments were correctly aligned in time among samples. Next, each sample was measured using a Velmex TA Tree-Ring measuring system. The measurement time series were fit with a highly flexible cubic spline, and each measurement was divided by the value predicted by the spline, which isolates systematic and diagnostic high-frequency, year-to-year variability. These high-frequency patterns, which meet the statistical assumption of serial independence were averaged within each lake to cancel individual, tree-level "noise" and amplify site-level patterns. This mean was then correlated against high-frequency patterns in the chronologies generated from

living trees; a highly significant ($p < 0.01$) correlation corroborates that the dead 'ghost forest' pattern has been correctly dated. The dead sample ring records were lagged backward and forwards through time by up to 100 years against the reference chronology and lagged cross correlation coefficients were generated (Figure 8). If the crossdating is correct, the correlation coefficient at the crossdated time (i.e., lag=0) should be conspicuously high relative to the other lagged correlation coefficients. Moreover, comparing these lakes with multiple chronologies from the Coast Range and even the western Cascade Mountains should provide the same dating result.

For each of our study sites, we used ^{14}C dating of a few strategic tree rings to 'wiggle match' with the ^{14}C calibration curve and confirm the slide chronology generated with dendrochronology (Reimer et al., 2004). We collected samples of organic material from landslide deposits and impounded the alluvial sediment fill to agument our landslide ages determined with dendrochronology to estimate the ^{14}C inheritance characteristic of western Oregon forests. This analysis is particularly useful for interpreting the ages of multitude landslides in western Oregon that lack dams and for which only deposits can be identified. We performed these calculations using OxCal—a commonly used program for generating chronologic models and probabilistically determining events from radiocarbon dates (Ramsey, 2009).
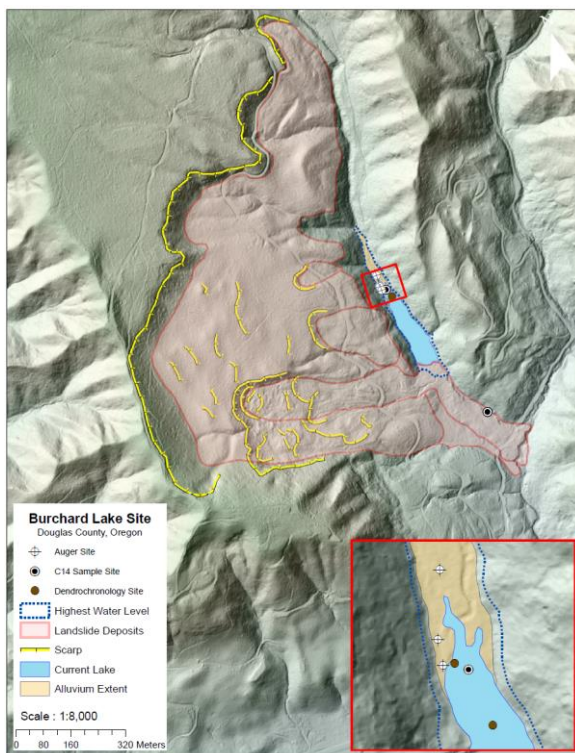
**Figure 7. Detailed site map of Burchard Lake site.**
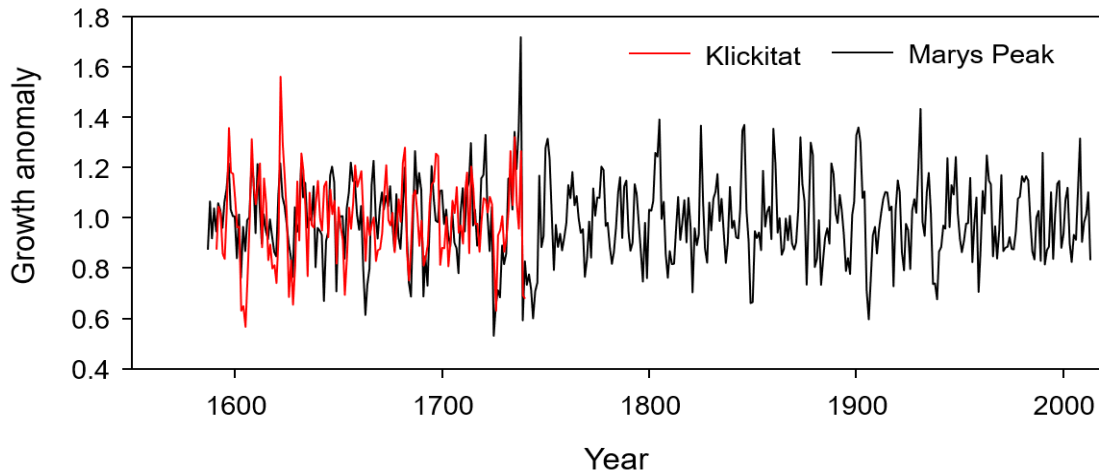
Figure 8. The mean of tree ring measurements from Klickitat Lake compared to a Coast Range (Marys Peak) chronology generated from live-collected samples. The Klickitat pattern is placed in time where its correlation with Marys Peak is conspicuously high; the probability of an error in this placement is less than 1 in 10,000.

2.3.3 GIS and Laboratory Analysis

We tested a geographical information system (GIS) method to estimate the landslide age at 3 sites: Drift Creek, Burchard Lake, and Wasson Lake. This method involved calculating the volume of sediment accumulated behind the landslide dam and the time-range (years) for that volume to be deposited based on typical erosion rates for the region (Butterfield, et. al., 2015). Three pieces of information are necessary to estimate the date range: 1) volume of sediment, 2) watershed area draining into the lake, and 3) estimated erosion rates for the landscape. For the latter, we used the average erosion rates generated via cosmogenic radionuclides by Balco et al. (2013) for the central Oregon Coast Range.

- Low Rate 0.05 mm/yr
- High Rate 0.2 mm/yr

The watershed areas were estimated using ARC GIS hydrology tools (Figure 9). A linear drainage network pre-sediment infill was assumed and a pre-sediment infill DEM was created for each site. The depth of the lake was also estimated and removed from the final volume calculation created by differencing the digital elevation models (DEMs).
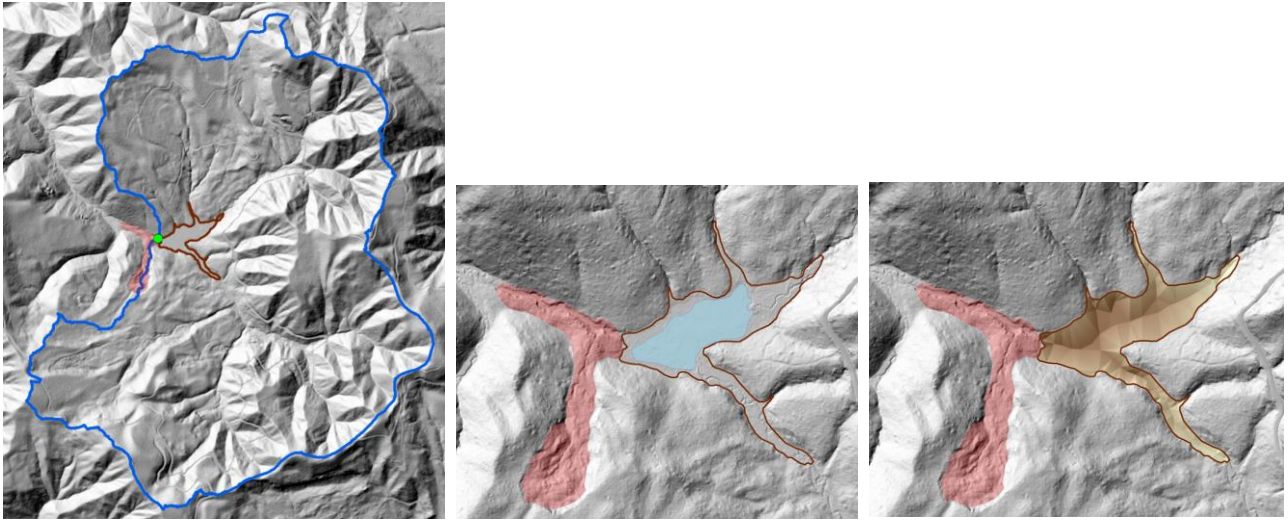
Figure 9. Map of watershed extent (blue outline) above the landslide Dam (red/pink area; left). Map of the sediment trapped behind the dam is outlined in dark brown with the lake (center). The modeled pre-sediment infill DEM (tan brown area, right) used to subtract from the current DEM (center) to estimate the sediment volume.

To confirm an event horizon correlates with the 1700AD event, we collected additional samples from lower event horizons to facilitate calibration with the ^{14}C curve (see below). Extraction of organic material and macrofossils for ^{14}C analysis was completed at the University of Oregon where we examined the stratigraphic samples and augered samples under a microscope for possible macrofossils and charcoal. The best 3-5 samples—based on amount of material and datable specimen—extracted from each event layer were selected for Accelerator Mass Spectrometry (AMS) dating at Lawrence Livermore National Laboratory's Center for Accelerated Mass Spectrometry (LLNL CAMS) ultimately leading to 50-60 radiocarbon samples from multiple event horizons from multiple different landslide deposits.

2.4 Results

We performed various levels of work at each of the sites (Table 1). These results are briefly summarized here. For each site, the results include a detailed site description (example below for the Lost Lake site *(see Figure 6 for location)*) and map (e.g. Figure 7).

Lost Lake Site Description

Date visited: 5/12/17

Access: Lost Lake is ~30 mins off Nehalem River highway on gravel roads; about 30-45 mins hike down from road to sediment fill

Description: The landslide deposit at Lost Lake site is currently impounding a lake and sediment is accumulating in a small delta into the lake from the upstream tributaries. The outlet is narrow (10 ft. wide) and ~20 ft. incised. The most recent landslide currently damming the valley is the reactivation of landslide debris as part of a larger landslide complex. The area upstream of the current lake level is super-saturated, muddy, marshy and boggy. There are many (>5) standing, tall snags both in the water and buried by sediment farther upstream.


Photo showing lake and standing snags. In background is forested landslide toe; to the left is the opposite valley wall; in the foreground is the aggraded fine grain sediment in 'delta' or marsh area aggrading into lake.

Samples: Radiocarbon sample were taken from two tree snags and sent to U of O; very good potential for dendro-wedging; unknown (no exploration) if there are candidates for increment boring on the toe, but the toe was forested. Sample Lost Lake-2 sample 1&2; sample 1 is intact outer rings; sample 2 is rotten bark

Interpretation: Site is very good candidate for dendro-wedges and further fieldwork, including hand augering and potentially use of an increment borer. Though the landslide damming the lake and sediment is reactivation, the larger landslide complex appears more subdued and subtle, and therefore older. The landslide debris that currently impacts drainage appears to be separate, distinct movement.

Sediment stratigraphy using augers and coring at multiple sites were logged. Figure 10 is an example of hand auger (HA) 1 at the Timber site (Figure 6). The Timber site had a man-made temporary "splash dam" installed at the site several decades ago. While at the site we noted cut pieces of wood in the drainage banks around 4 foot below the current surface. The Pt (peat) samples at 4'6" in HA-1 was interpreted as the paleosol formed before the modern anthropogenic (European settlement) time period. The Pt samples at 11' was interpreted as a possible landslide reactivation, while the Pt sample at 16' possibly reflects the original forest floor paleosol.
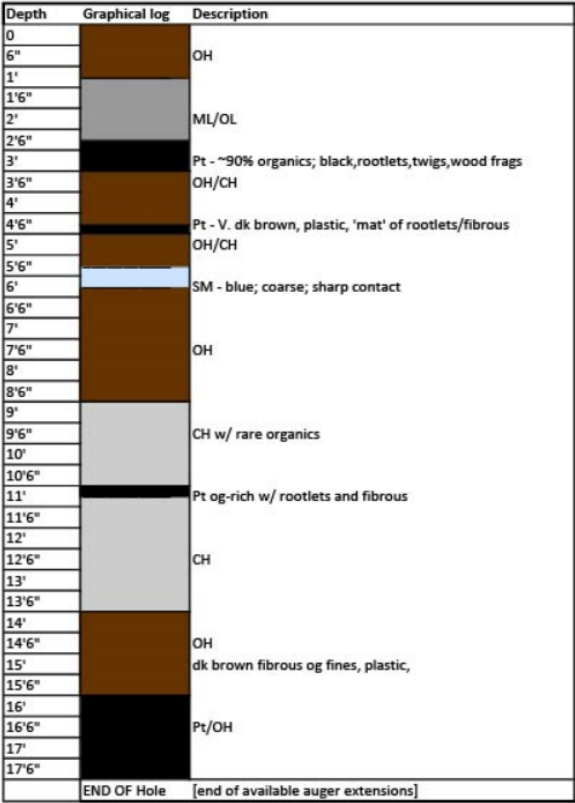
Figure 10. Subsurface log of HA-1 exploration at Timber site. The Pt (peat) samples at 4'6", 11', and 16' are interpreted as paleosols.

Table 2. Results of sediment volume rate analysis to estimate date range

GIS Object ID	Site Name	Estimated Date Range	Known dates or Dendrochronology
21	Wasson Lake	Low 549 yrs ago High 137 yrs ago	Dendro=182 yrs ago
22	Burchard Lake	Low 836 yrs ago High 209 yrs ago	
27	Drift Creek	Low 236 yrs ago High 59 yrs ago	Known failure date-1976 41 yrs ago

Landslide age estimates were generated using dendrochronology for Wasson Lake, OR (Figure 6), where a sample from a dead Douglas-fir contained 181 years of growth. These data were crossdated against established Douglas-fir chronologies from the OR Coast Range (Black et al., 2015), and indicate that the date of tree death was 1819 AD. The correlation between the Wasson Lake sample and a Douglas-fir chronology from Marys Peak was 0.38, a value that is highly statistically significant ($p < 0.001$) and conspicuously greater than correlations obtained when the time series was lagged back and forth through time. Thus, the synchronous pattern in Coast Range Douglas-fir is sufficiently strong to confidently date these samples, and the lifespan of dead-collected ('ghost forest') trees (>150 yr) provides the degrees of freedom necessary to establish statistical significance.

In addition to the Wasson Lake site, we also dated tree ring samples taken from Klickitat Lake (Figure 6) to 1751AD using the same technique. At that site, the presence of old-growth Douglas fir trees on the landslide deposit enabled us to narrow down the establishment of trees (>30 large diameter trees) that followed landsliding, to between AD1760 and AD1770. This result corroborates our analysis of the drowned trees which died in AD1751, and that between 10-20 years is often required for regeneration following a major disturbance. Finally, drowned snags in Lobster Lake (Figure 6) along the Alsea River catchment were dated to 1738AD or later. This constraint arises because the outer rings and bark were not identified so we cannot determine the exact year of death, but we can rule out ages prior to 1738AD.

Table 3. Results of C14 and Dendrochronology analysis.

Object ID	Site Name	Known dates or C14 or Dendrochronology
21	Wasson Lake	Dendro=1819AD
22	Burchard Lake	Prior to 1910
27	Drift Creek	Historical: 1976AD
	Klickitat Lake	Dendro=1751AD
	Lobster Lake	Dendro=1738AD or younger

2.5 Conclusions and Discussion

Based on our initial findings, we conclude that our method has the potential to date landslides that were triggered by the January 1700 Cascadia Earthquake. Our approach included multiple components:
- Lidar landslide mapping to identify potential study sites;
- Site reconnaissance;
- Sediment volume rate analysis to estimate date range;
- Carbon 14 dating to estimate landslide deposit;
- Detailed site mapping and sampling; and,
- Dendrochronology to establish year of landslide dam formation or forest establishment on landslide deposits.

Using this method, we determined that the most recent substantial slide activity associated with Wasson Lake, Klickitat Lake, and Lobster Lake, did not correspond to the January 26, 1700 Cascadia Earthquake event. We have identified numerous other sites which have the characteristics necessary to complete our analyses and have already initiated investigative work at these sites.

3.0 BIBLIOGRAPHY

The following publications resulted from the work performed under this award. One copy of each publication is attached. We also proposed and chaired Session 31: T245. Subduction Zone Coseismic Landslides at the 2017 GSA

Annual Meeting. A 2-day workshop on Cascadia Triggered Landslides was also organized and held in Eugene; the results of the workshop will be published soon. We will also publish a paper in a journal that focuses on our methodology as well as the preliminary results of this project.

Burns, W.J., Calhoun, N., Struble, W., Roering, J., 2017. Investigation of Cascadia Triggered Landslides, Program, Geologic Society of America Annual Meeting, Seattle, WA

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5.0 APPENDIX

Geological Society of America 2017
Session 31: T245. Subduction Zone Coseismic Landslides
Sunday, 22 October 2017, 01:30 PM - 03:30 PM The Conference Center - Tahoma 2
Advocates
William J. Burns, Oregon Department of Geology and Mineral Industries
Joshua Roering, University of Oregon

Alison R. Duvall, University of Washington
Kevin M. Schmidt, Geology, Minerals, Energy, & Geophysics Science Center

INVESTIGATION OF CASCADIA EARTHQUAKE TRIGGERED LANDSLIDES

Authors
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Nancy Calhoun, Oregon Department of Geology and Mineral Industries
Joshua Roering, University of Oregon
William Struble, University of Oregon

Coseismic landslides will likely account for much of the impact associated with the next Cascadia Subduction Zone (CSZ) earthquake. Despite the dozens of Cascadia subduction zone events in the Holocene, the connection between megathrust earthquakes and landsliding has not been established, much less systematically tested. To examine the role of coseismic landsliding in the Pacific Northwest, we have identified 219 deep-seated landslide complexes in the Oregon Coast Range (OCR) that exhibit the signature of recent movement as seen with airborne lidar mapping as well as upstream stream sediment in-fill caused by landslide dam impoundment. The goal is to sample and date detrital organics and tree snags and correlate with the CSZ earthquake record, specifically focusing on morphologically young landslide deposits that were likely triggered by the 1700AD event.

To date, we have visited and performed reconnaissance at 11 sites. We sampled tree snags and organic detritus, and performed carbon 14 dating at 7 sites. We extracted wedges from tree snags for dendrochronology from 3 sites. We are also performing subsurface exploration with hand augers at selected sites. Finally, detailed site maps and a summary of the findings will be created in a final report. We will present a summary of our work to date.

In June 2017, we held a workshop to facilitate, coordinate, and expand collective efforts to characterize the complex coseismic landslide history and hazards in the Cascadia region. The workshop consisted of a day of presentations summarizing the current knowledge base, followed by brainstorming on topics that need future attention effort. This was followed by a field day visiting one of the 11 sites. The four primary future research topics developed by the workgroup are: 1) a better understanding of the earthquake effects on the landscape, 2) a compilation of current knowledge of landslides triggered by subduction zone events, 3) use of landslide data to assist in constraining earthquake recurrence intervals, and 4) use landslides to constrain ground motion.

Geological Society of America 2017
Session 58: T236. Characterizing Cascadia's Earthquakes—Reexamining Open Questions about Cascadia Seismic and Tsunami Hazards
Sunday, 22 October 2017, 01:30 PM - 05:30 PM, The Conference Center, Yakima 1
Advocates
Robert C. Witter, U.S.G.S.
Lydia Staisch, Geology, Minerals, Energy, and Geophysics Science Center
Joan Gomberg

PROPENSITY FOR DEEP-SEATED LANDSLIDES IN THE OREGON COASTAL RANGES DURING CASCADIA MEGATHRUST EARTHQUAKES THROUGH DENDROCHRONOLOGICAL DATING OF LANDSLIDE-DAMMED LAKES (Invited Presentation)
Authors

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Seismic hazard analyses of the Cascadia subduction zone largely focus on primary threats posed by ground motion and tsunamis, and less attention is directed towards hazards posed by large, deep-seated landslides, which have the potential to overrun communities and dam rivers resulting in outburst floods. Despite an abundance of deep-seated landslides in the Oregon Coastal Ranges (OCR), no landslide has been conclusively linked to a Cascadia megathrust earthquake. While radiocarbon and surface roughness techniques provide compelling methods for dating landslides, they do not provide the precision to pinpoint definitively a landslide as coseismic. Landslide-dammed lakes with still-standing tree snags, or "ghost forests," present the novel opportunity to use dendrochronology for determining the year (and potentially season) of tree death and, therefore, the age of the lake-forming landslide dams that killed them. We have dated several landslide-dammed lakes throughout the OCR to ascertain the effect of coseismic ground motion. Given that the last subduction zone earthquake in Cascadia has been constrained to January 26, 1700, we restrict our search to relatively recent landslides as implied by morphologic properties determined by lidar. Using dendrochronology, we constrained the age of Wasson Lake and its associated landslide dam to 1819 AD, consistent with radiocarbon analysis. At Klickitat Lake, we generated a preliminary date of 1751 AD, though more dendrochronological measurements of drowned snags are needed.

Utilization of tree ring chronologies from the OCR to correlate measured ring thicknesses from snags at landslide-dammed lakes provides the precision required to date a landslide with minimal uncertainty. Radiocarbon may be used to corroborate the dendrochronology-derived dates, and calculated ages can be used to improve existing surface roughness dating techniques. While we have not yet found a lake that dates to 1700 AD, we have demonstrated that our enhanced ability to date landslide-dammed lakes using tree rings provides a preferred methodology for investigating the role of earthquakes in the landscape in Cascadia.